5.—THE GEOLOGY OF THE WATTLE FLAT AREA, CHITTERING VALLEY, W.A.

by

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ABSTRACT.

The area described lies in the northern part of the Chittering Valley and consists of an isoclinally folded series of metamorphic rocks of early Archaeozoic age, intruded by uralitized dolerites. These Pre-Cambrian rocks are overlain by later formations of ferruginous sandstone, laterite and yellow sand. The earlier sections of the paper are confined mainly to a factual account of the geology of the area and the petrography of the various rock types. In the discussion the mode of origin of the different rocks is considered. Regional metamorphism of sediments and granitization are thought to be the agents responsible for the formation of the metamorphic complex. It is likely that the ferruginous sandstone is part of the Bullsbrook Series of lacustrine sediments. The origin of the later yellow sand is not known with certainty.

I. INTRODUCTION.

The area examined is about 3½ miles square and lies in the upper reaches of the Chittering Valley. Its extreme south-western corner is situated a mile to the east of Cullala Siding, which is 62 miles north of Perth along the Midland Railway. It is accessible by road both through Bindoon and Mooliabeenee.

A few mixed farms are found in the broad mature valleys of the Brockman River (also known as the Chittering Brook) and its tributaries.

Geologically, the area consists of a series of isoclinally folded schists and gneisses overlain to the west by ferruginous sandstone and still later yellow sand. Simpson (1926) has described the occurrence of staurolite and kyanite within the area examined. The metamorphic rocks of Wattle Flat are the northerly extension of a similar complex occurring at Lower Chittering for which Miles (1938) proposed the name "Chittering Series." These rocks have also been described from Gillingarra, some 20 miles to the north of Wattle Flat, by Ivanac (unpublished MS.).

The Chittering Series is known to extend through Bullsbrook but a little further to the south it gives place to the Darling Range granites and gneisses. A rather similar series of metamorphic rocks, the "Jimperding Series" has been described at Malkup (Cole and Gloe, 1940), Jimperding (Prider, 1934), Toodyay (Prider, 1944) and Lawnswood (McWhae, 1948). The exact relation of the Jimperding to the Chittering Series is not known, since the country between Malkup and Lower Chittering has never been geologically examined, but both are thought to belong to one and the same complex, the Jimperding Series being a sandy facies and the Chittering Series a clayey facies.

The geological mapping of the area was carried out mainly by chain and compass traverses, which were tied to surveyed roads and fences plotted from the data of the Lands and Surveys Department and the Titles Office. The origin of the co-ordinate system used in this paper to describe the location of places mentioned is the south-west corner of Location 1166. A small section of the area was mapped by plane table and telescopic alidade. Most of the streams, laterite mesas and contacts of yellow sand and Pre-Cambrian rocks were mapped from aerial photographs, subject to frequent ground checking.

The earlier sections of this paper are confined, as far as possible, to a factual description of the geology of the area and the petrography of the different rock types. The conclusions, hypotheses and discussion arising from these facts are dealt with in the discussion section. Although this procedure involves a certain amount of reiteration, it is felt that this is warranted by the desirability of separating fact from theory.

The numbers mentioned in the petrographic descriptions refer to catalogued specimens in the collection of the Geology Department, University of W.A.

II. PHYSIOGRAPHY.

The main physiographic feature of the area is the Brockman River, a stream which flows to the south through a mature valley. Although its main directional tendency is from north to south, this stream makes an almost right-angled bend in the central part of the area and flows in an easterly direction for about a mile. However, if one consults a map showing the entire course of the Brockman River from its source just to the north of Wattle Flat to the point where it joins the Swan River at Upper Swan, it will be seen that its flow is almost directly north-south, and is evidently controlled by the regional strike of the Chittering Series (Jutson, 1934).

Except in the rainy season the flow of the Brockman River in this area is very sluggish and in the dry months of the year it ceases altogether. It is fed by a number of small tributaries which head near the high laterite mesas and flow only in the winter. The course of the main stream where it flows through the Pre-Cambrian rocks is characterised by a fairly broad alluvial plain, but where it flows through the later sand formation, this plain practically disappears and the watercourse becomes a dense ti-tree swamp. The courses of some of the minor streams through the alluvial plain are extremely meandering.

In addition to the tributaries feeding the Brockman River there exist in the yellow sand formation a few broad shallow water-courses, again heading in the laterite mesas. These are dry in all but exceptionally rainy periods.

The topography is usually hilly in the areas of Pre-Cambrian rocks and gently undulating in the yellow sand formation. A noteworthy topographic feature is that where there is alternation of bands of metasediments of different resistance to weathering (gneiss and mica schist, for example) there are a number of prominent sharp-crested ridges running parallel to the strike of the rocks. In the eastern part of the area however, where the rocks are more uniform in character, these parallel ridges are not present although the topography is hilly. The steep slopes of the majority of the hills, especially the parallel ridges, are characterised by abundant talus.

The intrusive dolerite dykes may be marked by small ridges or small depressions according to the resistance to weathering of the rocks they intrude.

III. THE FIELD RELATIONS OF THE ROCKS.

As previously mentioned the area consists essentially of a Pre-Cambrian metamorphic and igneous complex, unconformably overlain by ferruginous sandstone and a still later sand formation.

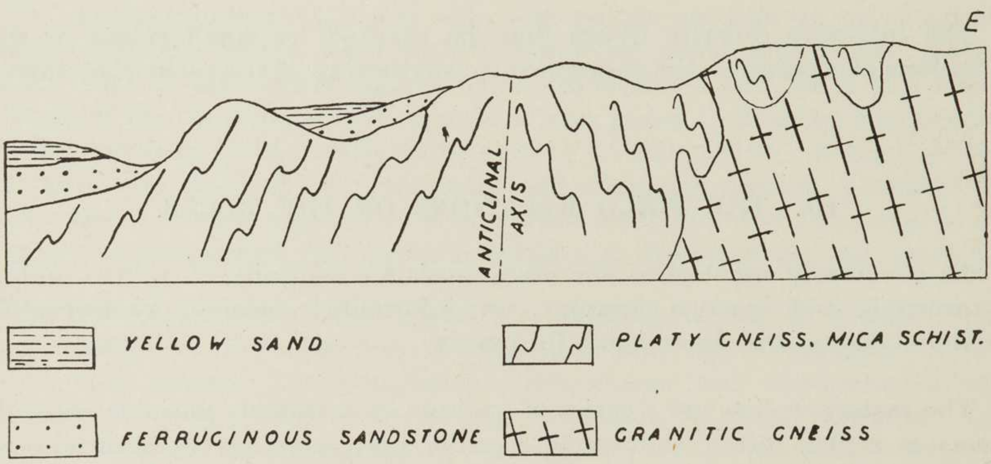
The metamorphics are a series of gneisses of extremely variable character, micaceous schists often containing kyanite and more rarely staurolite and garnet, hornblende schists and minor amounts of quartzite. Although large bands of quartzite are rare, small bands and lenses a few inches in width are frequent in the schists and gneisses. In addition to these original quartz lenses, later intrusive vein quartz is very abundant. Usually this is concordant with the country rock, but it is quite often seen transgressing it, following lines of weakness such as joints. Sometimes this quartz is found to contain well developed kyanite crystals.

Probably belonging to the same period of intrusion as the quartz veins, but much less abundant, are a few veins and dykes of pegmatite. The eastern part of the metamorphic complex consists of a gneiss, the coarse grain and uniform composition of which contrasts strongly with the finer grained varieties of gneiss in the west. The coarse-grained gneiss is not intercalated with mica schist, but does contain numerous basic lenses. The strike and dip of the rocks of the metamorphic complex is fairly constant, the strike being essentially north-south and the dip practically vertical.

The metamorphic complex is intruded by later dolerite dykes and epidote veinlets that are apparently associated with them. A reconnaissance survey made to a distance of about a mile to the east of the mapped area showed no change in the rock types, which are the coarse-grained gneiss with dolerite intrusions. However, the latter become much more abundant than in the mapped area.

The coarse-grained gneiss is traversed by a number of northerly trending shear zones in which the gneiss has been converted to a quartz-sericite schist. In the western part of the area these shear zones are much rarer, probably due to the presence of the incompetent bands of mica schist which would " take up " any shearing movement.

The ferruginous sandstone outcrops in the western part of the area and is invariably lateritised. Lateritised ferruginous sandstone and lateritised metamorphic rock are often found in close association and sometimes a single mesa consists of both types. From the field occurrence it appears that the contact of the ferruginous sandstone and the Pre-Cambrian metamorphics is irregular and that the former occurs as a thin discontinuous layer lying unconformably on the older rocks (text fig. 1). The outcrops of ferruginous sandstone shown on the map are those that were actually seen in the course of the traverses. However, as much of the laterite was mapped from aerial photographs, the extent of the ferruginous sandstone may well be greater than is shown.



Text fig. 1.
Diagrammatic section (not to scale) of the Wattle Flat area, showing the structure of the Pre-Cambrian complex and the relation of the later rocks to it.

The laterite, which is developed over both the Pre-Cambrian rocks and the later ferruginous sandstone, is not confined to any particular level or levels, but occurs at various heights from the highest laterite mesa, at an elevation of about 880 feet above sea level, to the banks of the Brockman River, about 600 feet above sea level (Plate II, fig. A). Furthermore, solid laterite cappings obviously formed in situ are sometimes seen dipping down towards the present valleys at angles of as much as 7°. The laterite mesas in the western part of the area often show 5 or 10 foot breakaways on their eastern margins, but slope gradually to the west until they grade into yellow sand, the contact not being marked by any breakaway.

The sand formation is found to the west of the main outcrops of Pre-Cambrian rocks and is believed to be younger than all the rocks previously mentioned. Its contact with the older rocks is extremely irregular and frequent large hills of Pre-Cambrian metamorphics stand out as prominent " islands " completely surrounded by a " sea of sand." For this reason it is thought that the thickness of sand in the area is not very great. The sand is generally a light yellow colour and its vegetation includes abundant banksias. Banksia (*Banksia sp.*) is completely absent from the vegetation over the Pre-Cambrian and because of this and the light colour of the yellow sand, the contact between the two stands out very clearly both in the field (Plate II, fig. B) and on the aerial photographs. Included in the sand formation are areas where the sand is greyish-white in colour with laterite nodules, and from which the banksia is absent. It appears that this sand is a fairly thin layer overlying laterite, and this fact possibly accounts for the difference in vegetation. Elsewhere greyish-white sand with the typical banksia association is found overlying the yellow sand. Whether or not there is any difference in age or origin of the two types of sand is a matter for speculation.

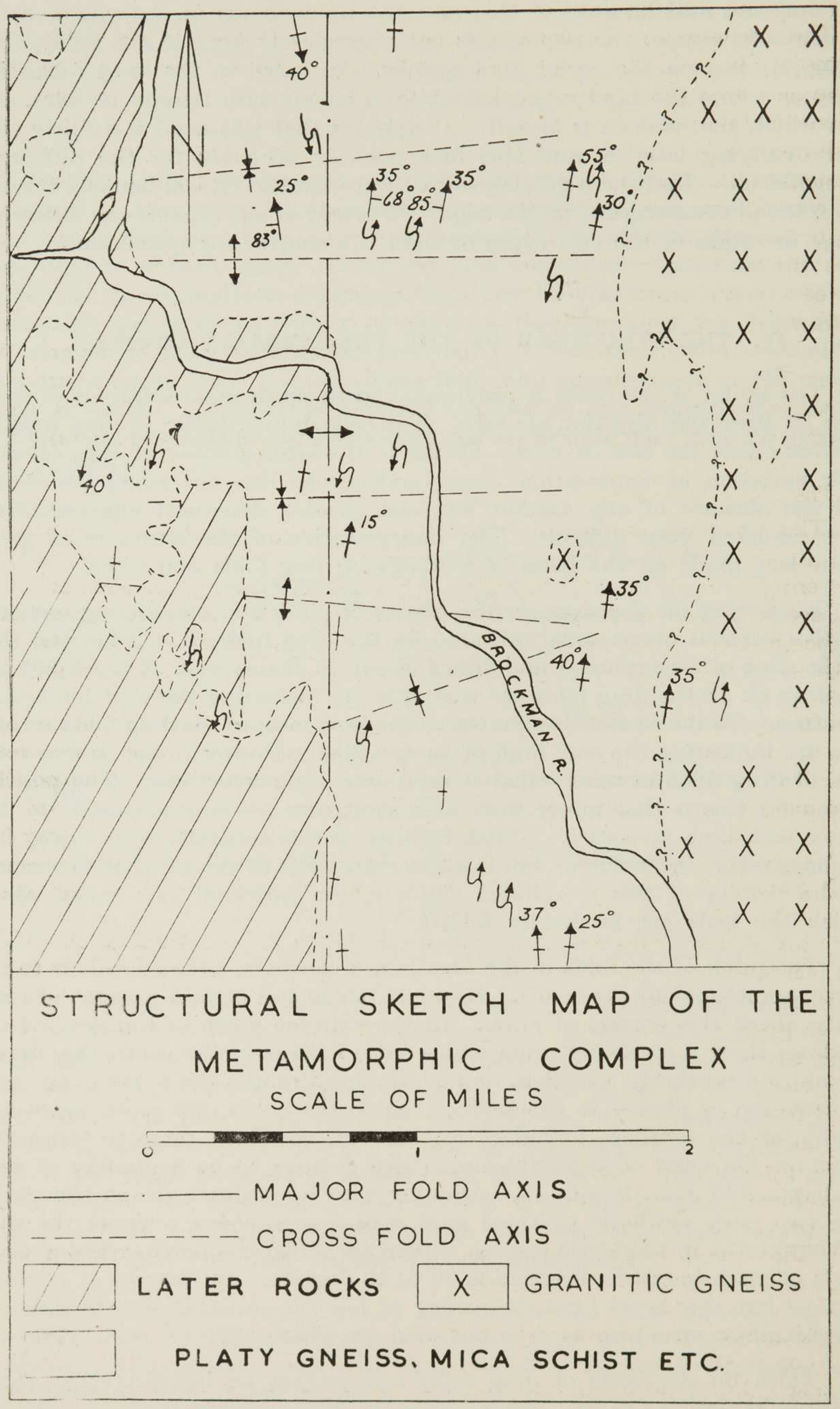
IV. THE STRUCTURE OF THE PRE-CAMBRIAN COMPLEX.

The strike of the rocks is practically north-south and variations of more than 12° from this direction are rare. The beds dip vertically, or very steeply, towards either the east or west. Owing to the large number of beds present, their variation in composition, their tendency to lens out along the strike, and the absence of any marker horizons, precise structural interpretations were rendered very difficult. The interpretation of the structure as given below was made on the basis of readings of drag folds and pitch.

Neglecting for the moment the effects of pitch and considering only the relative vertical movements indicated by the drag folds, it will be seen that to the west of a meridional line drawn about 20 chains west of Block 805 the readings on all the drag folds are west side up, indicating the west limb of an anticline. To the east of this line the readings on most of the drag folds are east side up, indicating the east limb of an anticline. However, one or two readings of drag folds in mica schist showed west limb structures. The possible reason for this is that minor west limb structures are superimposed on the major east limb structure. Such features as this naturally render drag fold readings rather inconclusive, but it seems reasonable to assume that somewhere in the vicinity of this meridional line a major anticlinal axis exists, about which the beds are isoclinally folded.

The pitch of the folds in the area is not constant, sometimes it is to the north, sometimes to the south. However, there is a certain amount of regularity about this change of pitch. In the extreme north of the area all the readings show a southerly pitch and a little further to the south the pitches are all in a northerly direction, and continuing towards the south of the area a succession of pitches to the south, then to the north, the south again and finally, at the southern boundary of the area, the rocks pitch to the north. Thus on the basis of these readings there appears to be a number of east-west crossfold axes, five in all, beginning with a synclinal axis in the north. The two most southerly of these axes appear to coalesce towards the east, as the pitches in the south-eastern corner are all to the north. The average angle of pitch in either direction is 30 to 40 degrees. In one case it is nearly vertical but this rapid local steepening of pitch is probably due to some eccentric minor structure as it is not seen anywhere else.

Thus, on the basis of drag folds and pitches an interpretation of th possible structure of the metamorphic complex has been given. In th absence of a greater number of readings the positions of the various axe cannot be fixed with certainty, however the structure of the area can be succinctly stated as a series of metasediments, isoclinally folded in a north-south direction and traversed by a number of east-west cross folds (text fig 2).



Text fig. 2.

Structural sketch map of the metamorphic complex at Wattle Flat.

V. PETROGRAPHY.

A. THE PRE-CAMBRIAN ROCKS.

1. The Gneisses.

The gneisses are the most abundant rocks developed in the area. On the map (Plate I) they have been divided into granitic gneiss outcropping in the east and platy gneiss which occurs in the west. These are two convenient field names that serve to indicate the difference between the two types. In the extreme west of the Pre-Cambrian complex a gneiss occurs, which, although it exhibits certain differences from the typical granitic gneisses, is best classed with them. On the whole the granitic gneiss possesses a reasonable uniformity of texture and composition, whereas the platy gneiss is much more variable and includes several types. The contact shown on the map between the two gneisses is purely arbitrary, and indeed it is almost impossible to draw an accurate contact. To the north it is largely obscured by laterite and in the extreme south by alluvium. In the central portion of the area the western approach to the granitic gneiss is marked by a close intercalation of the two types rather than a definite contact. This state of affairs is maintained over a considerable distance, sometimes as much as half-a-mile.

(a) *The Platy Gneisses.*

These occur as bands intercalated with micaceous and basic schists and vary in width from 10 chains or more down to a few inches. As the schists frequently lens out along their strike, two separate bands of gneiss may often coalesce to form a single one. The platy gneisses vary widely in texture and composition and rapid variations across the strike are common. Such features make it impossible to map separately the different types of platy gneiss.

In various parts of the area, especially near the contact with the granitic gneiss, the various types of platy gneiss contain large porphyroblasts of oligoclase and microcline, which transgress the gneissosity and stand out prominently against the fine-grained groundmass.

A rather puzzling feature is the extremely fine grain of many of the platy gneisses. It would be expected that, under the high grade metamorphism to which these rocks have been subjected (as evidenced by the presence of kyanite), a coarser texture would have resulted from recrystallisation. The obvious answer to this seems to be that the later shearing that has evidently taken place was the cause of this fine grain. Whilst mylonitization of some of the platy gneisses has occurred, many of the finest grained rocks contain large subhedral felspar porphyroblasts which are comparatively unaltered and which transgress the banded structure. Although these felspars show small fractures they do not show augen structure. It would seem impossible for these felspars to retain this form while cataclasis reduced other grains to a fine groundmass, especially as the porphyroblasts show inclusions of this groundmass. Hence it appears that even under the high-grade metamorphism that prevailed, the fine grain of these rocks was preserved. It will be seen later that these porphyroblasts are thought to have been introduced after the formation of the original rock.

Although on the basis of mineralogical composition distinct types can be recognised among the platy gneisses, these grade imperceptibly into one another. The type specimens described below, however, are sufficient to give a full petrographic account of the different varieties.

(i) Quartz-oligoclase-microcline-biotite gneiss (24264)*.—This is a light-grey, even-grained rock with a distinct fine banding due to the alternation of thin biotitic and quartzo-felspathic bands and also to the parallel orientation of biotite flakes.

In thin section there appears to be, in addition, a parallelism between the long axes of quartz and felspar grains and the gneissosity. There is a tendency for some of the crystals to show peripheral granulation, other evidence of strain effects being the marked undulose extinction of the abundant quartz grains and the irregularity of the twinning in some of the plagioclase grains.

Albite-oligoclase and microcline are both abundant and myrmekite is also present.

The biotite shows strong pleochroism with X greenish-brown and Z very dark-brown. It appears to be altering to chlorite and iron ores.

One or two large subhedral grains of magnetite are present and minute needles of apatite and zircon occur in accessory amount.

Several varieties of the above type exist. Some specimens are quite rich in muscovite, others may show an absence of microcline or a paucity of biotite. A common variant is that in which microcline and albite-oligoclase occur as relatively large porphyroblasts. This association of porphyroblastic microcline and plagioclase has a genetic significance and a separate description of this rock (25704) is warranted.

This is light-coloured, fine-banded rock with occasional felspar porphyroblasts up to 3 mm. in diameter, transgressing the banding. Under the microscope it is seen to consist of a very fine groundmass of quartz and felspar grains, a mere fraction of a millimetre in size, parallel lenses of quartz grains of much larger size (averaging about 0.5 mm. in diameter) and occasional porphyroblasts of microcline and albite-oligoclase. These are squarish subhedral crystals, not augen, and they appear to have been formed by growth in the solid. The microcline porphyroblasts are larger and more abundant than those of the plagioclase. They are slightly kaolinized and contain frequent inclusions of quartz, muscovite, biotite and magnetite. The albite-oligoclase is clear, with albite twinning poorly developed. When present at all it is very irregular in shape.

Biotite is fairly abundant, occurring either as small subhedral to anhedral isolated flakes, or as much larger aggregates associated with muscovite, chlorite and iron ores. It appears to be altering either to a greenish pleochroic chlorite or to a dark opaque mass of iron ore and chlorite. The muscovite, often associated with the biotite, shows a faint greenish pleochroism.

The accessories are magnetite, ilmenite altering to leucoxene, with lesser amounts of zircon, apatite and sphene.

(ii) Garnetiferous gneiss.—In the fine-grained biotite-rich gneisses garnets find abundant and widespread development. Generally they occur in elongated bands showing a paucity in biotite, indicating that the garnet has developed at the expense of this mineral. A curious feature seen in the field is that these garnetiferous bands transgress the directed structure of the biotite gneisses in which they are developed at an angle of about 5 to 10 degrees—they have probably been developed along the traces of fracture cleavage.

* Specimen numbers refer to the General Collection of the Department of Geology of the University of Western Australia.

25667 is a light-coloured rock with large idioblastic garnets up to 2 cm. in diameter in a fine-grained groundmass of quartz and felspar with occasional biotite flakes. Microscopic examination shows that the groundmass is even-grained, with an average grain size of about 0.25 mm. The garnet exhibits typical sieve structure, being crowded with quartz inclusions. It is pale pink in colour and is traversed by an irregular system of fractures along which extensive iron staining has occurred. Together with the garnet, quartz and albite-oligoclase, mostly untwinned, make up the bulk of the rock. Biotite, occurring in anhedral flakes, is not very plentiful. It is usually associated with the garnet, either around its margins or included in it, and shows varying degrees of alteration to chlorite which modifies its pleochroic scheme. Some of this chlorite shows anomalous blue interference colours under crossed nicols. Scattered grains of magnetite sometimes included in the garnet, and a few tiny zircons, are present.

(iii) Quartz-oligoclase-biotite-hornblende gneiss (24256).—This is a very distinctly banded rock with alternating quartzo-felspathic and ferromagnesian-rich layers up to 2 mm. thick. In thin section, parallel alignment of biotite flakes and hornblende crystals is evident. Quartz and plagioclase, sometimes showing twinning, occur as anhedral grains. The plagioclase is clear, with frequent inclusions of small subhedral quartz grains. These two minerals are also associated in a myrmekitic intergrowth. The refractive index of the plagioclase is greater than balsam but less than quartz, its optical character is positive with $(+)2V = 88°$. The maximum extinction angle perpendicular to the 010 cleavage is about 5°. This data indicates an albite-oligoclase of composition about Ab_{85} An_{15}.

Elongated subhedral flakes of biotite up to 1 mm. in length are abundant. It shows strong pleochroism with X light-brownish green and Z very dark brown. Subhedral prisms up to 2 mm. long and basal sections of hornblende are also plentiful. It is often closely associated with the biotite and contains numerous inclusions of plagioclase, epidote and quartz. The pleochroic scheme is X brownish green, Y deep brownish green and Z deep blue-green, absorption $Z = Y > X$ and Z to $c = 19°$. Granular sphene is common, often forming small lenses which are usually associated with hornblende, biotite or epidote. The epidote shows similar occurrence but is less abundant than the sphene. Microcline is present in accessory amount only, other accessories being magnetite, apatite and zircon. Chlorite, pseudomorphous after hornblende, is a common secondary mineral.

(iv) Quartz-oligoclase-microcline-biotite-epidote gneiss (24261).—This is a prominently banded, medium-coloured rock, showing alternation of fairly thick biotitic and quartzo-felspathic layers. Examination of the thin section shows that the parallel orientated biotite flakes are associated with epidote. Although most of the quartz grains are only a fraction of a millimetre in size, occasional pockets of larger grains occur. Albite-oligoclase is found both as fine grains and as porphyroblasts up to 2 mm. in length. These show alteration, being crowded with fine granular zoisite. The porphyroblasts occasionally contain inclusions of the fine-grained quartzo-felspathic groundmass and some seem to be replacing microcline. They appear either to push aside or sharply truncate the groundmass constituents and their appearance indicates that they have grown in the solid state. Some of them have suffered small scale fracturing and bending of the albite twin lamellae. Myrmekite is present in small amount sometimes bordering microcline grains. The microcline, although less abundant than the plagioclase, is found as porphyroblasts and sometimes in the groundmass.

Biotite flakes averaging about 0.5 mm. in length are plentiful. The pleochroic scheme is the same as in the previously described gneisses and the mineral shows alteration to chlorite. Closely associated with, and included in the biotite is a pale yellowish green pleochroic epidote comprising about 15 per cent of the rock. Granular sphene is another common associate of the biotite. One or two basal sections of hornblende, altering to chlorite are present. Accessories include apatite, magnetite, calcite and zircon.

(b) *The Granitic Gneisses.*

Although certain minor variations do occur, generally speaking the granitic gneiss exhibits a uniformity that is not seen in the platy gneiss.

24250 is a grey, coarse-grained rock with a rather indistinct banding due to parallelism of occasional biotitic bands. It is crowded with felspar porphyroblasts up to 1 mm. in length, giving the rock a texture approaching granitic. Under the microscope these porphyroblasts are seen to be contained in a very fine-grained groundmass of quartz and felspar, with frequent parallel lenses of larger quartz grains. The general appearance of the rock is rather reminiscent of 25704 described above, the chief point of difference being the much greater proportion of porphyroblasts to groundmass in this specimen. The porphyroblasts contain inclusions of the fine-grained groundmass. Microcline, which shows a certain amount of kaolinization, is more abundant than the albite-oligoclase. The latter shows surface alteration to flecks of fine sericite. Greenish biotite, altering to chlorite and iron ores, and also a very pale green muscovite are present. Magnetite and ilmenite altering to leucoxene are the most common accessories, others being apatite, zircon and sphene.

24259 is a very similar specimen except that the banding is less distinct and the fine-grained groundmass less abundant.

Frequently the granitic gneiss is richer in ferromagnesians than the specimens described above. Dark clots and stringers, which under the microscope prove to consist of aggregates of biotite, chlorite and iron ores, are orientated parallel to the gneissic structure and give the rock a distinctly banded appearance. Small veinlets of deep purple fluorite are common in some of these gneisses and this mineral may prove useful in correlation of the gneisses.

In the western central part of the metamorphic complex a gneiss (25639d and 25640) occurs which in the field is similar to some of the granitic gneisses to the east. However, microscopic examination shows it to differ from the typical granitic gneisses in a number of respects and a separate description is warranted. Furthermore, this gneiss contains inclusions of a peculiar suite of basic rocks which will be described later.

In hand specimen it is coarse-grained and porphyroblastic with a very distinct banding due to alternation of quartzo-felspathic and thick biotitic layers. In thin section small amounts of a very fine-grained groundmass appear, as well as the large porphyroblastic crystals. Albite-oligoclase is by far the most abundant felspar, microcline being much less abundant and occurring in much smaller grains, usually occupying interstices between the large albite-oligoclase porphyroblasts and sometimes being enclosed by them. Myrmekite also is quite plentiful. Biotite is present in stout euhedral to subhedral crystals up to 2 mm. in length, often containing inclusions of quartz, plagioclase, apatite, epidote and zircons with pleochroic haloes, and showing strong pleochroism from greenish brown to very dark brown. The accessory minerals are calcite, sphene, apatite and epidote.

In the field this coarse-grained gneiss is seen to contain small concordant lenses of a fine-grained platy gneiss consisting of quartz, albite-oligoclase, microcline and biotite. A small pegmatite vein is seen transgressing the strike of the coarse-grained gneiss.

The peculiar feature about it is that the gneissic banding and the biotitic layers responsible for this banding continue right across the pegmatite vein, indicating that the latter is the result of gaseous emanations rather than a liquid intrusion.

Specimens of all the different gneisses in the area were examined under ultra-violet light for fluorescent effects. It was thought, following the recent work of Wilson (1947, p. 201 ; 1950) that the felspars of different varieties might have shown different fluorescent effects, forming some basis for correlation and possibly giving a clue to the mode of origin of these rocks. The results were rather disappointing, the only rocks containing fluorescent felspars being the coarse-grained gneiss just described. Under the ultra-violet light the albite-oligoclase showed a faint but definite pink and the quartz a bluish colour. The zircons in the biotite appeared as bright orange specks. The felspars of the pegmatite vein referred to and the gneiss both showed this pink fluorescence, indicating probably that the gneiss and pegmatite were genetically related. However, the felspars of a large pegmatite dyke a couple of chains distant showed no fluorescence, which may mean that this dyke is unrelated to the gneiss. Apart from suggesting that there may be some difference in origin between this gneiss and the main body of granitic gneiss to the east, the results of the fluorescence tests were too indefinite to warrant any conclusions being drawn.

2. Lenses in the Granitic Gneiss.

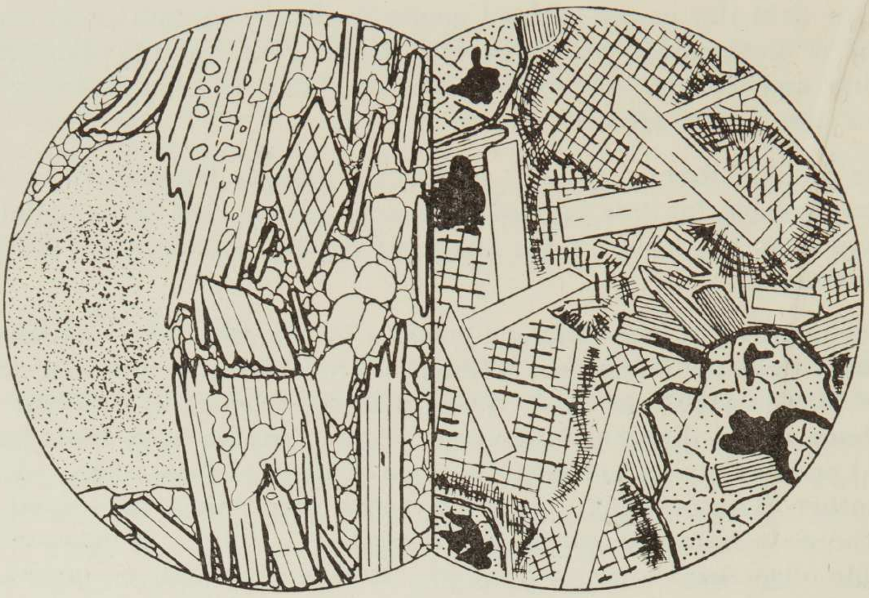
The frequent occurrence of lenses of platy gneiss in the granitic gneiss has already been referred to. In the extreme eastern part of the area a lens of the epidote-rich variety of the platy gneiss is found and at another spot a quartzite lens occurs. In addition to these there are three types of basic lenses described below. All the different types of lenses are concordant with the gneiss.

(a) *Hornblendic basic lenses.*

These occur frequently in the granitic gneiss and one specimen was found within the platy gneiss. They are dark-coloured, schistose rocks occurring as bands up to a chain or more in width and several chains in length. In the field they were mapped as sheared dolerites but petrographic examination suggests that they are of a different origin. Invariably they contain hornblende crystals in parallel alignment and usually fairly large porphyroblasts of albite-oligoclase. They are in fact hornblende schists, but it is proposed to reserve this name for a somewhat different group of rocks.

24238 (text fig. 3A) is a dark-coloured, schistose rock. It is by no means uniform in texture, for although the most abundant constituent is hornblende, there are quite sizeable light-coloured bands of quartzo-felspathic material and in addition scattered felspar porphyroblasts up to 2 mm. or more in diameter.

In thin section this heterogeneity becomes even more evident and the rock is seen to consist of hornblende-rich and quartz-felspar-rich aggregates which show a crude alternation of layers. There are, in addition, the porphyroblasts of felspar which appear to displace and often include the other minerals.



Text fig. 3.
Two types of basic lenses. Fig. 3A is a hornblendic basic lens, showing hornblende laths in parallel alignment, a fine quartzo-felspathic aggregate, and saussuritized porphyroblastic oligoclase. Fig. 3B is a garnetiferous biotite pyroxenite, showing ophitic texture with plagioclase laths included in pyroxene which is altering to fibrous hornblende around its margins. Other constituents seen are idioblastic garnets, cored by magnetite, and biotite laths.

The prophyroblasts include saussuritized albite-oligoclase and microcline, which occurs as smaller grains and is much less abundant than the plagioclase. The hornblende is usually in the form of parallel, elongated subhedral laths of varying size. Some of the larger crystals are markedly poikiloblastic containing numerous inclusions of fine quartzo-felspathic material. It is strongly pleochroic with X yellowish green, Y deep brownish green and Z deep bluish green, with the absorption Y > Z > X. Chlorite from the alteration of hornblende is quite plentiful. It is biaxial negative with (—)2V about 30°. Associated with the hornblende are occasional aggregates of greenish chloritized biotite. Small amounts of magnetite changing to hematite and skeletal crystals of ilmenite altering to leucoxene are also associates of the hornblende. The quartzo-felspathic part of the rock, other than the porphyroblasts already mentioned, consists of a very fine granular aggregate with lenses of quartz grains of considerably larger size. It is indeed very similar to the groundmass of the platy gneisses. Apatite is present in the rock in accessory amount.

(b) *Chlorite-biotite schist* (25672b):

This is of much rarer occurrence than the hornblende lenses and was in fact, found at only one place. It is a dark-coloured micaceous rock with a schistose structure and is traversed by quartz veins arranged parallel to the schistosity.

Microscopic examination shows it to consist of long subhedral laths of biotite, alternating and associated with elongated aggregates of chlorite. The biotite is pleochroic according to the scheme—X very light brown and Z very dark brown—and it contains numerous inclusions of granular sphene and apatite, also a little quartz and epidote. The chlorite is pleochroic from pale green to emerald green and under crossed nicols shows an anomalous greyish blue interference colour. Also associated with the biotite are small amounts of muscovite. The quartz veins are composed of grains of average size 0.5 mm., which have undulose extinction and in most cases serrated edges, indicative of crushing.

(c) *Garnetiferous greenstones and associated biotite norite.*

Occurring as lenses in the previously mentioned coarse-grained gneiss from the western central part of the metamorphic complex are a few peculiar basic rock types which appear to be genetically related. The largest of these lenses is about 4 chains wide and contains what appears to be a large drag-fold in which a definite pitch to the south is seen. Rock types present in this lens are a dark, medium-grained, even-textured rock which might be referred to as a hornblende diorite, passing on its margins into a hornblende schist. This schist does not appear to have any genetic significance other than the fact that it had developed from the massive rock due to marginal stress. A garnetiferous biotite pyroxenite is also present. The hornblende diorite just referred to is not given a separate description here because, other than the absence of garnet, it is similar in all respects to a garnetiferous biotite amphibolite which is found underlying the laterite a few chains to the south and which is described below.

A few chains to the west of this large basic lens there are two smaller lenses consisting respectively of biotite norite and garnetiferous biotite pyroxenite. The biotite norite was not found at any other place in the area but about a mile to the north-east of these lenses a specimen of garnetiferous biotite pyroxenite was collected from a lens in the platy gneiss.

The garnetiferous biotite pyroxenites are in hand specimen (25652) almost identical with dolerite and under the microscope they show a distinct ophitic texture, the only apparent difference from a dolerite being the presence of idioblastic garnets and fairly plentiful brown biotite. Even so, the temptation is strong to call them dolerites of abnormal composition, possibly contaminated. However, in view of their apparent genetic association with the rock types mentioned and the fact that the folded and pitching structure referred to above occurs in these rocks, they are best regarded as basic lenses in the gneiss. A discussion of their possible modes of origin will appear below.

25652 (text fig. 3B) is a typical *garnetiferous biotite pyroxenite.* It is a dark, fine even-grained, massive rock which under the microscope shows an ophitic texture. Plagioclase appears as strongly normally zoned, clear, subhedral laths. Albite twinning is seen in almost all the grains, the maximum extinction angle in sections perpendicular to the 010 twin plane being 28°. The optical character is positive with a variable 2V. It appears as though the average composition is near Ab_{50} An_{50} (labradorite). Clinopyroxene occurs as subhedral grains invariably altering to hornblende around the margins. It shows good cleavage, a fine schiller structure and twinning along the 100 plane. Inclusions of plagioclase are present. It is optically positive with (+)2V about 40° to 45° but variations from this occur. It is possibly a diallagic ferro-augite. Also present and sometimes coring the clinopyroxene is a small amount of hypersthene. Its pleochroism is not marked, it is optically negative with 2V about 75° and is therefore an iron-rich variety.

Hornblende is seen both as a fine border around the pyroxene and as quite large anhedral grains showing a good amphibole cleavage. It is pleochroic with X pale green, Y olive green and Z green and $Z \geq Y > X$. Garnet is fairly abundant as pink idioblasts up to 1 mm. in diameter, almost invariably cored by magnetite associated with brown biotite. It also contains small inclusions of altered pyroxene and plagioclase. Anhedral grains of quartz and needles of apatite are present in accessory amount.

24239 is a *garnetiferous biotite amphibolite* which in hand specimen is a dark, medium-grained, massive, even-textured rock. Under the microscope it is seen to consist mainly of anhedral grains or laths of albite-oligoclase with marked normal zoning, and granular to poikoloblastic aggregates of hornblende, which contain abundant inclusions of plagioclase and less frequent magnetite and garnet. Also included in the hornblende are a number of hematitic aggregates. Often found as cores in these are tiny relics of pyroxene, which give an optically positive figure with a moderately large 2V. From this it seems as though the hornblende has developed from the pyroxene. Garnet is quite plentiful as pink idioblasts up to 2 mm. in diameter. It is almost always cored by magnetite and contains in addition, hornblende and plagioclase inclusions. Brown pleochroic biotite is found usually associated with the hornblende. Chlorite altering from hornblende is present and accessories are quartz and apatite.

25656 is a *biotite norite* which in hand specimen is a dark-coloured, medium-grained, even-textured rock. In thin section the rock is seen to consist essentially of subhedral laths of labradorite showing frequent albite and Carlsbad twinning, pyroxene and hornblende. Hypersthene is the most abundant pyroxene, occurring as anhedral to subhedral grains showing very fine schiller inclusions. The extinction is mostly parallel but deviations of a few degrees from this are seen. It is faintly pleochroic from pale pink to pale green and it is optically negative with 2V about 60°, which puts it into the iron-rich category. It is altering to hornblende around its rims. Also present, occurring in the same manner, but much less abundant than the hypersthene, is optically positive clinopyroxene, with $Z \wedge c = 45°$. Hornblende is abundant occurring both as fine borders around the larger pyroxene grains and as granular aggregates. It is pleochroic with X pale green, Y brownish green, Z olive green and absorption $Y > Z > X$ and $Z \wedge c = 26°$. Biotite occurs as subhedral flakes up to about 0.5 mm. in length, generally associated with the amphibole. It is strongly pleochroic with X pale straw yellow and Z dark brown. Anhedral grains of magnetite, sometimes changing to hematite, are also usually associated with hornblende. Apatite is present in accessory amount.

3. Shear Zones in the Gneiss.

As mentioned before these are confined mainly to the granitic gneiss in the east and the platy gneiss immediately adjacent to it. They have a general northerly trend and their effect is to reduce the gneisses to quartz-sericite-chlorite schists (25690).

This is a light reddish-grey rock with a pronounced schistose structure. It shows an alternation of fine micaceous bands with bands and lenses of crushed quartz. Muscovite occurs both as fine sericite aggregates and small subhedral flakes with a good cleavage. It is intimately associated with a greenish biotite, most of which has altered to chlorite. Ilmenite altering to leucoxene and magnetite changing to hematite are quite abundant accessories.

4. The Mica Schists.

Next to the gneisses these rocks are the most abundant in the metamorphic complex. They occur in bands varying from a few feet to several chains in width. On the whole the bands of mica schist are not as wide as those of the gneisses and they have a greater tendency to lens out along their strike. Here it may be mentioned that for obvious reasons the smaller outcrops of schist are not shown on the map.

The variations in the mica schist are mainly mineralogical and they can be conveniently classified according to the minerals present into mica schists, garnet-mica schists, staurolite-mica schists and kyanite-mica schists. Apart from the mica schists, by far the most abundant of these are the kyanite-mica schists, staurolite being found in a few specimens only and garnet in contrast to its abundant development in the platy gneisses, was found in only one specimen.

On one of the field excursions, at which the author was not present, a rock was collected, which on examination proved to be a quartz-biotite-epidote schist. It was found as loose boulders in an area that is shown on the map as granitic gneiss near the contact with platy gneiss. A later inspection of the area failed to reveal any trace of this rock and so its field relations are not known, but it is evidently not of widespread occurrence. A petrographic description of the rock is given but in view of the above facts no speculation is made as to its mode of origin.

(a) *Mica Schist.*

The mica schists, and indeed the other members of the metapelitic schist group, may contain both biotite and muscovite, or either one of these minerals may be absent.

24271 is a quartz-muscovite-biotite schist and is typical of the mica schists. It is a light-coloured, very schistose rock consisting of muscovite and biotite bands intercalated with lenticular pockets of quartz, the grains of which average about 0.5 mm. in diameter and show undulose extinction. The biotite is pleochroic with X almost colourless and Z brown. The absorption in both directions is less than is the case in all of the rocks previously described. It occurs as elongated flakes intimately associated with similar shaped muscovite flakes. Small zircons with intense pleochroic haloes are common inclusions in the biotite.

(b) *Garnet-mica schist.*

25695, a garnet-muscovite schist, is the only representative of this group found in the area. It is an iron-stained very schistose rock, with layers of muscovite and quartz and frequent idioblasts of garnet about 0.5 cm. in diameter. Quartz occurring as anhedral grains with undulose extinction and average size of 0.5 mm. is the most abundant constituent. The elongated aggregates and flakes of muscovite are often very much iron-stained. The large garnets are also iron-stained and are crowded with quartz inclusions, which curiously enough, show much more regular outlines than the quartz grains that are not included in the garnet, almost as though the rock had once been in a plastic state and that the garnets had protected their quartz inclusions from the later cataclastic movements that had been responsible for producing the irregular margins of the rest of the grains. Magnetite changing to hematite is an abundant accessory in the rock, and tiny apatites and zircons are also present.

(c) *Staurolite-mica schist.*

25658 is a quartz-muscovite-biotite-staurolite schist and consists of bands of muscovite and biotite flakes intercalated with sizeable veins and pockets of quartz. Large idioblasts of staurolite up to 2 cm. or more in length and containing quartz inclusions are common. Biotite, altering to chlorite and iron ores and pleochroic from light green to dark brown occurs as elongated subhedral flakes together with lesser amounts of muscovite. The staurolite is crossed by irregular fractures and frequently contains quartz inclusions. It is optically positive with 2V about 88°. It is strongly pleochroic according to the scheme X very pale yellow, Y pale brown and Z reddish-brown, with absorption Z > Y > X. Accessory minerals are magnetite changing to hematite and apatite.

(d) *Kyanite-mica schist.*

In the majority of cases the kyanite-mica schists are similar to the mica schists except that they contain abundant large bladed crystals of kyanite up to 3 cm. in length. In some specimens, however, the kyanite crystals are much smaller and less evident in hand specimen.

(e) *Quartz-biotite-epidote schist* (24274).

This a dark grey finely banded schistose rock with quartz veins both parallel and oblique to the schistosity. Under the microscope bands of quartz are seen alternating with very fine biotitic bands containing epidote and sphene. The grain size of the quartz varies from a small fraction up to about 1 mm. in length. The larger grains are usually much longer than they are wide, and their long axes parallel the schistosity. The biotite, pleochroic from pale greenish brown to very dark brown occurs as numerous extremely fine layers parallel to the schistosity. Associated with the biotite are bands composed of granules of epidote, with sphene present to a lesser extent. Irregular aggregates of pale green chlorite also occur in the rock.

5. Quartzite.

Quartzites are comparatively rare in the metasediments of Wattle Flat. A band in the north of the area, about a chain wide and extending for a known distance of half-a-mile and a smaller lens in the granitic gneiss constitute the only sizeable outcrops encountered.

25705 is a greyish coloured, distinctly banded, highly quartzose rock. Under the microscope the banding is seen to be due to alternation of quartzose layers containing numerous small laths of biotite with layers consisting almost entirely of quartz. The banding is also due in some respect to the parallel alignment of the biotite laths, and to the alternation of bands of different grain size. Quartz comprising about 80 per cent of the rock is found as anhedral grains averaging 0.25 mm. in diameter and showing serrated edges and undulose extinction. Biotite and muscovite occur as minute laths, which are confined to certain bands and which are in parallel alignment. These laths often continue through or are included in the quartz grains. The biotite is pleochroic from pale greenish brown to very dark brown and is more abundant than the muscovite. Accessories include a small amount of untwinned albite and ilmenite altering to leucoxene.

6. Amphibolite and Epidote Amphibolite.

These rocks are found at only one place (157 N., 45 W.) where they are closely associated and intercalated with platy gneiss (hornblendic variety).

24248 is an amphibolite, similar in many respects to the hornblende schists, a group of rocks which are described below, but in view of some of its characteristics, and its association with the epidote amphibolite, it is thought to be of different origin. In hand specimen the rock is medium to coarse grained with a marked schistose structure. In thin section it is seen to consist of about 85 per cent of hornblende occurring as euhedral basal sections and prisms up to 0.5 cm. in length, and containing abundant inclusions of magnetite and a few of plagioclase. It has rather a peculiar pleochroic scheme with X pale green, Y emerald green and Z blue, absorption $Z = Y > X$ and $Z \wedge c$ of 29°, which is rather high for an amphibole. Basic andesine comprises about 10 per cent of the rock and the accessories include apatite, epidote and sphene.

24249 is an epidote amphibolite and consists of a dark green part consisting almost entirely of hornblende laths, included in which are many irregular shaped light green patches of granular epidote varying in size up to about 6 cm. in length. These epidotic patches contain isolated laths of hornblende. In thin section it is seen that these two minerals together with magnetite comprise the entire rock, no quartz or felspar being present. The hornblende laths are subhedral, varying in size up to 2 mm. and show a very rough subparallel alignment. Pleochroism is marked with X light yellow-green, Y green and Z blue with absorption $Z = Y > X$ and $Z \wedge c$ of 27°. The similarity of optical properties of the hornblendes of this and the previous specimen is apparent. The epidote occurs as aggregates of fine grains, varying in size up to 0.5 mm. It is non-pleochroic and optically negative with 2V about 88°. Magnetite is fairly abundant, occurring as anhedral grains of varying size.

7. Hornblende Schist.

This is quite abundant as bands, rarely exceeding a chain in width, intercalated with the platy gneisses and mica schists. Usually they do not persist for any great distance along their strike. Petrographically they show a uniformity of texture and mineral composition.

25687 is a dark-coloured, even-grained rock with a marked schistose structure due to alternation of felspathic and hornblendic bands and to parallel alignment of hornblende prisms, which vary in length up to 3 mm. In thin section the hornblende is seen to be strongly pleochroic with X pale yellow-green, Y olive green, Z bluish green, absorption $Z > Y > X$ and $Z \wedge c$ of 23°. It often contains inclusions of quartz, oligoclase, sphene or epidote. Some of it has altered to chlorite. Albite-oligoclase occurs in anhedral grains elongated parallel to the schistosity and frequently shows albite twinning. It is fairly clear and may contain a few inclusions of hornblende or epidote. Anhedral grains of quartz are of fairly frequent occurrence, granular bands of epidote and sphene are common whilst magnetite and apatite are present in accessory amount.

8. Uralitized quartz dolerite.

This is found as dykes, of average width about a chain, intruding the earlier rocks. Generally they trend in a N.N.W. direction.

24242 is a dark green, fine even-grained rock. In thin section it is evident that is has suffered considerable alteration but a sub-ophitic texture is preserved. Basic andesine occurs as markedly zoned subhedral laths with a faint brown colour and shows general saussuritization. The pyroxene appears to have been entirely replaced by a light greenish, fine, fibrous uralitic hornblende. Accessories include ilmenite altering to leucoxene, anhedral flakes of brown biotite, often associated with the ilmenite and a few small anhedral grains of quartz.

9. Breccia.

This rock was found as loose boulders on the surface at 95S., 30E., an area that consisted of platy gneiss and mica schist and it is not known whether its relation to these rocks is concordant or discordant.

In hand specimen it is a dark green, fine grained, fragmental cherty looking rock without any trace of banding. In thin section the fragmental nature of the rock is even more striking. It consists of extremely fine angular fragments of quartz and felspars embedded in a groundmass of fine fibrous amphibole and chlorite. Large irregular patches of granular sphene and opaque leucoxene are present. Pale greenish yellow pleochroic epidote is quite abundant and the whole rock is traversed by a network of minute veinlets of quartz and felspar. The felspar is optically positive and its refractive index is approximately the same as Canada balsam and so it is probably an albite-oligoclase. It shows marked zoning but no twinning. Also present is a colourless mineral of low birefringence, refractive index less than balsam, optically negative with 2V about 65°, which is possibly orthoclase. The hornblende usually occurs in fine fibrous form but one or two larger poikiloblastic crystals up to 1 mm. in length are present. It shows pleochroism X pale yellow-green, Y olive green, Z blue-green and absorption $Y > Z > X$. Much of the hornblende shows partial or complete alteration to chlorite. Numerous minute needles of apatite are present in accessory amount.

B. THE LATER ROCKS.

1. Ferruginous Sandstone.

The ferruginous sandstone is a fine-grained non-bedded, unfossiliferous, reddish-brown rock. The alumina and iron oxide content of the rock is very high and the detrital quartz grains are well sorted, the majority of them being retained on the 115 Tyler mesh with a smaller amount on the 250 mesh. Larger grains than this, however, are present in the ferruginous sandstone and in fact quartz pebbles are sometimes found in the lateritised ferruginous sandstone.

An examination of the finer grains which compose the majority of the detritals, shows that they are angular with vitreous and fractured surfaces. Sphericity determinations show no significant variation, the sphericity of the majority of the grains being between 0.70 and 0.85 on the visual scale of Rittenhouse (1943).

Heavy minerals were separated from the grains retained on the 115 and 250 mesh sieves. They are fairly plentiful and include :—

Ilmenite : which is by far the most abundant of the heavy minerals and is invariably altering to leucoxene. Generally, the grains are poorly rounded with ragged edges.

Hematite : rather similar in occurrence but less abundant than ilmenite. It shows a reddish colour in reflected light.

Magnetite : this is much less abundant than ilmenite or hematite. Occasionally it occurs as well rounded grains.

Kyanite : the most plentiful of the non-opaque minerals is kyanite. It is found mainly as subhedral prisms and does not show rounding.

Staurolite : is quite abundant in irregular shaped grains, pleochroic from pale yellow to yellowish-brown.

Zircon : almost invariably occurs as euhedral grains, which are colourless or slightly purplish and often zoned.

Andalusite : is found as irregularly shaped grains.

Muscovite : one or two irregular flakes are present.

Tourmaline : a few unrounded grains showing strong pleochroism are present. Both blue-grey and brown varieties are seen.

Sphene : one or two irregular grains only are present.

2. Laterite.

The chief variations in the laterite are in structure (which may be cellular or pisolitic), relative proportions of iron oxides and aluminous materials and in the presence or absence of quartz pebbles. Generally the laterite overlying the ferruginous sandstones can be distinguished from the laterite overlying the Pre-cambrian, in that the former contains included ferruginous sandstone fragments.

In the north-east part of the area laterite from a high mesa overlying platy gneiss, exhibits polar magnetic properties, and compass readings made at this point show very marked deviations. Moreover some fragments are capable of attracting and repelling the compass needle, that is, they possess North and South poles. Some specimens collected from outcrops in situ show different polarity on their upper and lower faces (the upper being a south pole). Other specimens from nearby do not show any marked magnetic effect.

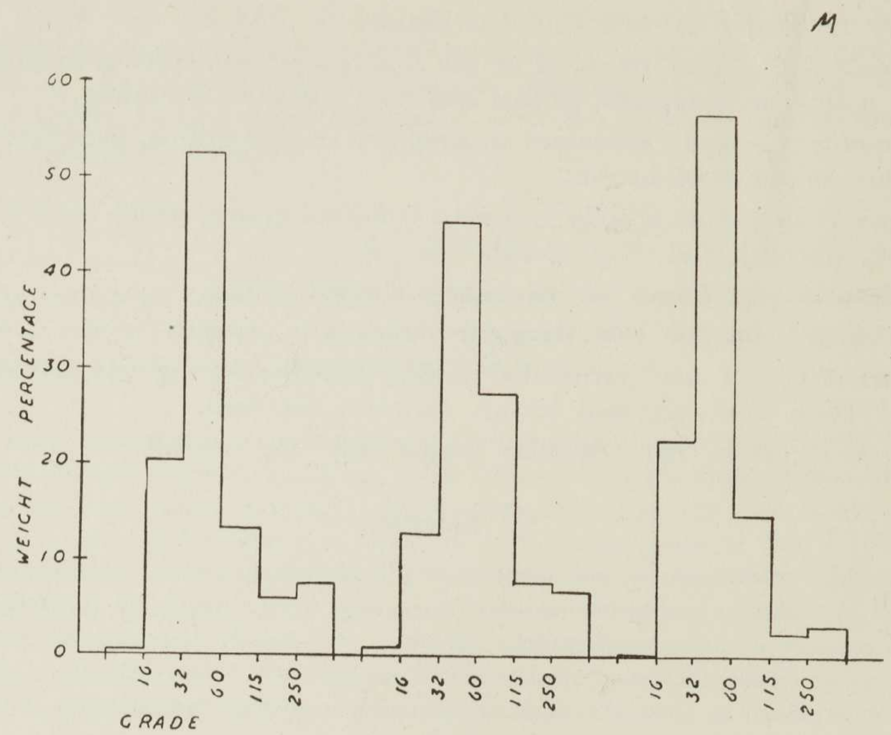
Two other laterite outcrops in the area, further to the west, cause a deviation of the compass needle but this is less marked and it is not known whether these laterites possess polar properties.

The rocks underlying the polar magnetic laterite are platy gneisses intruded by a dolerite dyke, but whether these can be in any way responsible for the magnetic phenomenon is very doubtful.

3. The Yellow Sand Formation.

Mechanical analyses and heavy mineral separations of three different samples of sand from different places in the area were made. In addition the quartz grains were examined for roundness, sphericity and surface texture. All three samples showed a marked similarity of properties and a separate description of each is not warranted.

In all three specimens the maximum amount (45 to 55 per cent) of grains are retained on the 60 Tyler mesh (text fig. 4 for histograms). The sorting coefficients of the samples vary from 1.3 to 1.4 so that according to Trask's classification they are well sorted. However, the sorting is not as good as in the ferruginous sandstone. The coefficients of geometrical quartile skewness of the three specimens are 0.79, 0.94 and 1.10 so that in two of them the maximum sorting lies a little on the coarse side of the median diameter and in the other a little on the fine side.



Text fig. 4.

Histograms showing the mechanical composition of the three sand samples examined.

Variations in roundness and surface texture of the grains can be summarized as follows :—

Retained on 16 mesh (1–2 mm.).—All the grains are frosted on the surface and are fairly well rounded (between 0.5 and 0.6 on the visual scale of Krumbein, 1941).

Retained on 32 mesh (½ to 1 mm.).—The great majority of the grains show frosting and fair rounding, but a few are vitreous with rough fractured surfaces.

Retained on 60 mesh (¼ to ½ mm.).—Three types of grains can be distinguished, the fairly well rounded grains with the frosted surfaces seen in the coarser grades, fairly well rounded grains with a polished surface imposed on a frosted surface and finally, comprising about 50 per cent of the fraction angular vitreous grains with a rough fractured surface.

Retained on 115 mesh (⅛ to ¼ mm.).—Practically all the grains are the vitreous fractured type and only a few show frosted surfaces.

Retained on 250 mesh (1/16 to ⅛ mm.).—Almost all the grains are the vitreous fractured type.

Thus it can be seen that the rounded and frosted grains tend to occur in the coarser grades and the vitreous fractured grains in the finer grades. There does not appear to be any gradual transition from one type to the other.

The sphericity of the grains of various grades shows no significant variation. In all grades the sphericity of the grains varied from about 0.70 to 0.90 on the visual scale of Rittenhouse (1943).

Heavy minerals were separated from the 60-115 and 115-250 mesh grades. The weight percentages of the three samples constituted by these heavy minerals were 0.1 per cent, 0.16 per cent and 0.28 per cent. On the whole the strongly magnetic fraction shows a marked angularity of grains whereas most of the non-magnetics are fairly well rounded. The minerals present include :—

Ilmenite : is the most abundant heavy mineral present. All the ilmenite shows some alteration to leucoxene, and in some cases this alteration is complete. Where there has been little alteration the grains are mostly angular with rough surfaces, showing percussion marks, but the grains that have completely altered to leucoxene are much more rounded.

Magnetite : is not as abundant as ilmenite, but nevertheless is quite plentiful, occurring as angular grains.

Hematite : is present as fairly well rounded grains.

Kyanite : is the most abundant of the non-opaques. It occurs as prismatic grains, the ends of which are generally fairly well rounded. Quartz inclusions are often present in the mineral.

Staurolite : the grains are mostly angular, especially in the finer fraction.

Zircon : the majority of the grains are colourless or slightly purple, well rounded and zoned. However, some euhedral zircons, containing small inclusions are also present.

Epidote : is seen as irregular grains with a marked yellowish green pleochroism.

Rutile : is present as dark reddish-brown grains showing varying degrees of roundness.

Tourmaline : the grains are dark brown, show strong absorption, but are not very abundant.

Andalusite : one or two well rounded grains showing pale pink pleochroism are present.

Hornblende : a few dark green grains are present.

Pleonaste : occurring as blue-green isotropic grains is rare.

VI. DISCUSSION.

A. THE PETROGENESIS OF THE PRE-CAMBRIAN ROCKS.

1. The Gneisses and the Basic Lenses in the Granitic Gneiss.

The platy gneisses, exhibiting as they do such features as intimate intercalation with mica schists, infinite variety of texture and mineralogical composition and rapid change in character across the strike, must be regarded as being of sedimentary origin. Originally they were a series of arkoses, arkosic sandstones and greywackes, which have been subjected to intense folding and regional metamorphism, with the resultant formation of para-gneisses. The variations in the gneiss are due to facies variation in the original sediments. Hornblende and epidote gneisses, for example, are probably derived from sediments that contained a certain amount of dolomitic and calcitic material, whereas biotite-rich gneisses are due to the presence of a greater proportion of shaly material in the original sediment.

What then is the origin of the granitic gneiss ? Before answering this question, certain important facts may bear re-emphasis. Firstly, the strike and dip of the granitic gneiss is in all places essentially the same as that of the platy gneiss and associated metasediments. Furthermore, the granitic gneiss contains a number of lenses which include platy gneiss, quartzite and various types of basic rock. In all cases these lenses have a concordant relation to the enclosing granitic gneiss. Thirdly, no sharp contact is seen between the granitic and the platy gneiss, rather is there an intercalation of the two types. Finally, there is development in the platy gneiss, especially near the contact with granitic gneiss, of a number of porphyroblasts of microcline and albite-oligoclase. As mentioned previously, these transgress the bedding, contain inclusions of the groundmass and generally exhibit features indicative of their having grown in the solid state. Also, microscopic examination shows that the same fine-grained groundmass that is characteristic of some of the platy gneisses, is present in lesser amount in the granitic gneiss. Indeed, certain specimens of platy and granitic gneiss appear to differ only in the much greater proportion of porphyroblasts in the latter.

All of these facts are best explained by assuming that the granitic gneiss was originally a part of the same series of sediments that are now represented by the platy gneisses and micaceous schists. During the period of orogeny these sediments are thought to have been subject to a process of granitization which followed in the wake of the folding and regional metamorphism. The term " granitization " is used here in the sense that it is used by Read (1944), viz., " the process by which solid rocks are converted to rocks of granitic character without passing through a magmatic stage." This granitization included introduction by ionic diffusion of a large amount of felspathic material, resulting in the formation of the numerous porphyroblasts of microcline and albite-oligoclase. Parts of the country rock that escaped this granitization remained as lenses of platy gneiss in the granitic gneiss. The development of porphyroblasts extended beyond the granitic gneiss and is seen to a lesser extent in the surrounding platy gneiss. Associated with the granitization, probably as an end phase, was the formation of the ubiquitous quartz veins and the pegmatite dykes. These are thought to have been formed by metasomatic replacement rather than the intrusion of an end phase of a granitic magma (Ramberg, 1949). There is evidence (outlined above) that at least one pegmatite vein could not have been due to a magmatic intrusion. Indeed, it does not appear necessary to ascribe a magmatic origin to any of the gneisses in the area.

Before leaving this subject of granitization, the origin of the basic lenses will be considered. In the field the hornblende lenses were first thought to be sheared dolerites, but petrographic examination indicates that this is very unlikely. The hornblende-rich parts alternate with fine quartzo-felspathic aggregates very similar to the groundmass of many of the platy gneisses and there is also a development of large plagioclase porphyroblasts up to 2 mm. in diameter. It is inconceivable that such features could have developed from the shearing of a dolerite. Furthermore, the presence in one or two specimens of porphyroblastic microcline, together with biotite, indicates a larger amount of potash than a normal dolerite contains. If then, the rocks are not sheared dolerites, we must look for another mode of origin.

Reynolds (1946) has suggested that the process of granitization involves a preliminary stage of enrichment in the cafemic constituents and alkalies. These elements are driven ahead of the main front of granitization as a basic front. If the front of granitization outstrips this basic front the basified rock will be caught up as concordant xenoliths in the granite.

It is thought possible that the basic lenses in the gneiss at Wattle Flat may have been formed in such a way, and that a basic front caused the formation of the hornblende, together with sphene, which is quite abundant in many of the specimens. These newly formed minerals were intercalated with the fine quartzo-felspathic groundmass of the original sediment. Subsequently these basic rocks were caught up in the advancing front of granitization and it was at this stage that development of the porphyroblasts occurred.

Basic lenses containing porphyroblasts similar to those developed in the enclosing gneiss are common features of gneissic complexes the world over. Numerous examples have been quoted by Reynolds (1946).

At this stage it may be argued that if one is to regard these basic lenses as products of a basic front, might not those platy gneisses that are rich in hornblende epidote or sphene, be a result of the same process, rather than the regional metamorphism of dolomitic and calcitic sediments ? This must be regarded as a possibility. In this connection Reynolds (1947) discusses the substance of a paper by Lapadu-Hargues, appearing in the *Bull. Soc. Geol. France*. Lapadu-Hargues considers that the various metamorphic grades are not isochemical as has been generally regarded and finds a variation exists in the concentrations of the various elements in rocks of different regional metamorphic grades. This he thinks is due to the difference in mobility of the various elements under metamorphic conditions. Iron and magnesium, for example, being the most mobile, become concentrated in the lowest metamorphic grade. Reynolds compares this with the " basic front " concept. If these theories are valid, then the relation between granitization, with its complementary basification, and regional metamorphism, may be very close.

How now are the garnetiferous greenstones and associated types to be explained ? It has been pointed out that despite the ophitic texture of some of them and general resemblance in hand specimen to dolerites, they could hardly be regarded as such.

Reynolds (1946) discusses the metasomatic alteration of pelitic and related rocks that are associated with granite and gives a number of examples. She points out that many granitic and granodioritic masses are walled and roofed by basic rocks which are also found as inclusions in the granite, and considers that these are due to the enrichment of pelitic sediments by elements of the basic front which travels ahead as the vanguard of a front of granitization. In many cases these basic rocks may assume the composition and appearance of igneous rocks for which they may be easily mistaken. As an example she draws attention to the Flamanville Granite of Normandy described in 1893 by Michel Levy, who was much impressed by the presence of basic hornfelses containing pyroxene, amphibole, garnet, plagioclase, orthoclase, anorthoclase and sphene. At certain points these hornfelses exhibited an increase in grain size and passed to rocks resembling true dolerites, and granular diabases within which ophitic texture is locally developed. Reynolds quotes from Michel Levy " Nous voyons naître ainsi en petit, et par métamorphisme de contact du granite, des roches basique éruptives analagues aux diabases ouralitisées du Beaujolais, du Lyonnais, de la Loire et du Pûy-de-Dôme."

With the exception of orthoclase and anorthoclase, all the minerals mentioned above by Michel Levy are present in the garnetiferous greenstones at Wattle Flat, and his remarks on texture find a close parallel in these rocks. The point that arises from this discussion is the fact that a rock may exhibit all the textural characteristics of a typical igneous rock, including an ophitic relation between the plagioclase and pyroxene, and yet still be of sedimentary origin.

It is possible that the garnetiferous greenstones and associated biotite norite of Wattle Flat may be the result of metasomatic alteration of pelitic sediments by elements of a basic front that was associated with the granitization which is thought to have been responsible for the formation of the surrounding granitic gneiss.

An alternative hypothesis to this is that these rocks represent an early basic lava, intruded as a sill, contaminated with aluminous material and subsequently folded and regionally metamorphosed along with the sediments. However, the presence of kyanite in nearby micaceous schists indicates that during the folding of these sediments a high directed pressure prevailed. If these basic rocks were due to contamination of an early lava, it is difficult to see how such typical anti-stress minerals as hypersthene and clinopyroxene, which they contain, could survive in the presence of such a high directed pressure. The presence of these minerals indicates that the rocks in question were formed after the most intense folding and directed pressure had waned, that is about the middle or end stages of the main orogeny, and about the time of formation of the synchronous gneiss.

Before leaving this subject, mention should be made of the gneiss enclosing these garnetiferous greenstones. It was seen that this gneiss exhibits fluorescent effects not observable in other gneisses. This may be due to a local difference in chemical composition rather than a difference in age or origin. Furthermore, although granitization usually involves an enrichment in potash, no porphyroblastic microcline is seen in this gneiss. However, the gneiss is abnormally rich in the potash-bearing mineral biotite, and paucity of microcline may not necessarily mean paucity in potash. This might well be proved by chemical analysis.

2. The Other Metasediments.

The various mica schists and quartzites have undoubtedly been derived from the regional metamorphism of shaley and sandy facies respectively, in the original sediments.

The amphibolite, in view of its association with the epidote amphibolite and petrographic differences from the hornblende schist (which include the greater abundance of a different hornblende, the presence of a much more basic plagioclase and a rather different texture), is best regarded as differing in mode of origin from the hornblende schists. The epidote amphibolite may have originally been an intraformational breccia or septarian nodule containing dolomitic, clayey and ferruginous material, while the associated amphibolite may have been an impure dolomite.

3. Hornblende Schist.

In view of the uniformity of composition of the hornblende schist, the fact that unlike the hornblendic lenses in the gneiss, they show no admixture of gneissic material or development of porphyroblastic felspar, and the fact that their contact with the surrounding rocks is always sharp, they appear to have been derived from the regional metamorphism of tholeiitic sills or lava flows. This hypothesis is consistent with the fact that in the first down-buckling of a geosyncline, before the most intense folding has occurred, the sediments are subject to concordant intrusions of basic magmas (Umbgrove, 1947).

4. Uralitized Quartz Dolerites.

All the later doleritic intrusions at Wattle Flat show marked uralitisation of the pyroxene and sausuritisation of the plagioclase. Rarely is any of the original pyroxene seen. The cause of this is thought to be a deuteric effect, rather than a shearing, which would cause chloritisation and not uralitisation of the pyroxene (Harker, 1932).

These dykes were apparently intruded during a period of crustal tension. Often in geosynclinal evolution a diastrophic sequence may be recognised, involving firstly orogeny, or folding, due to horizontal compression, followed by a broad uplift (epeirogeny) and finally a period of fragmentation due to tension (taphrogeny). It may be that the intrusion of these dolerite dykes was associated with this final taphrogenic period. If this were the case, the age of the dolerite would best be regarded as Archaeozoic, since the taphrogenic phase would follow fairly soon, geologically speaking, after the main orogeny which is thought to be of early Archaeozoic age. However, this is pure conjecture, and it is quite possible, although certainly not definite, that these dykes are the same age as those described by Prider (1941) from Armadale, which intrude the Cardup Series of Nullagine age. Prider (1948) considers that all of the quartz dolerites are of late-Proterozoic (post Nullagine) age.

5. Breccia.

In view of its obscure field relations the origin of this peculiar rock remains unknown. Its fragmental texture rather suggests that it may have been a fine-grained basic tuff, contemporaneous with the metasediments, but if this is the case, it is difficult to see why the hornblende has not crystallised as large, parallel orientated, subhedral prisms as it has done in the hornblende schists. Furthermore, there is no trace of directed structure. A more likely hypothesis is that the rock is part of a breccia dyke, produced by intense crushing due to the intrusion of a dolerite dyke. Apart from this crushing, the dolerite magma seems to have exerted a metasomatic effect resulting in the formation in the rock of hornblende, epidote and leucoxene. The chief objection to this theory is that no dolerite dyke was seen in the immediate vicinity, although this does not mean that one does not exist. Moreover, as the rock was found as loose boulders on the side of a hill, it has probably been transported from its place of formation.

B. THE LATER ROCKS.

1. Ferruginous Sandstone.

The occurrence of ferruginous sandstones or ferruginous grits has been described at Wongong-Cardup (Thomson, 1942), Ridge Hill (Prider, 1948), Upper Swan (Fletcher and Hobson, 1932) and Lower Chittering (Miles, 1938). At Bullsbrook ferruginous sandstones and grits, lithologically similar to the Wattle Flat rock, occur associated with leaf-bearing shales (Clarke, Prider and Teichert, 1944). It is likely that all these sandstones were formed contemporaneously.

Prider (1948) has made mechanical, heavy mineral, roundness and surface texture analyses of a specimen of ferruginous sandstone from Ridge Hill, which is similar to the ferruginous sandstone at Wattle Flat. The main points of difference between the two specimens examined are the finer grain, and consequent smaller proportion of rounded and frosted grains, and the better sorting of the Wattle Flat specimen, which also shows a greater proportion of kyanite in the heavy mineral assemblage.

Such heavy minerals as kyanite, staurolite, zircon and andalusite, that occur in the Wattle Flat ferruginous sandstone indicate that its distributive province lay in the metamorphic rocks to the east.

It is most likely that this ferruginous sandstone is part of a series of Mesozoic sediments which are found at Bullsbrook (the Bullsbrook Series) and extend north underlying marine Upper Cretaceous (at Gingin and Dandarragan) with a slight unconformity. These sediments consist of a series of breccias, conglomerates, grits, sandstones, silts, shales and clays, all of freshwater lacustrine origin. The exact age of these rocks is not known. A few poorly preserved plant remains occur in shales at Bullsbrook, and from an examination of them Walkom considered that they seemed to be more indicative of a Lower Cretaceous age than any other (Clarke, Prider and Teichert, 1944, p. 275). However, what appears to be a continuation of this series is found at Gingin, where the plant remains are of Jurassic age.

Thus it appears that the ferruginous sandstone of Wattle Flat was formed by the deposition in a lacustrine environment of the erosion products of the Precambrian rocks lying to the east. Its age is probably either Jurassic or Lower Cretaceous.

2. Laterite.

Laterites from parts of the Darling Range near Perth have been described by various authors. Simpson (1912, p. 400) writes :—" Broadly speaking, the laterite of Western Australia may be divided into two classes :—

(1) Primary Laterite (true laterite, high-level laterite), formed in situ out of soluble material derived from the weathering rock immediately underlying it.

(2) Secondary Laterite (lateritite, low-level laterite), composed largely of the mechanically transported fragments of primary laterite."

Woolnough (1918) considers that these two levels of laterite are of the same age and owe their difference in elevation to block faulting after the formation of the laterite.

Later authors in describing laterite in the Darling Range have followed Simpson in the use of terms " high and low-level laterite " to denote respectively the laterites of the higher and lower regions of the Darling Scarp.

Prider (1948) found that at Ridge Hill the laterite occurred at two distinct levels, the high-level laterite at an elevation of 700 feet above sea-level and the low-level laterite on the Ridge Hill Shelf at elevations of between 220 and 280 feet above sea-level. Furthermore, he found that whereas the high-level laterite was formed over the Pre-Cambrian complex the low-level laterite was formed over ferruginous sandstone. Both laterites, he considered, were true laterites or primary laterites formed in situ but he regarded the low-level laterite as having been formed later than the high-level laterite.

At Wattle Flat the same two varieties of laterite as described by Prider from Ridge Hill are recognised, viz., the laterite formed over the Precambrian and the laterite formed over the ferruginous sandstone. However, whereas at Ridge Hill the two types differ in elevation by about 400 feet, at Wattle Flat they are closely associated and sometimes are found at different parts of a single mesa. The occurrence of laterite at random levels and its tendency sometimes to dip towards the valleys has already been mentioned.

Fletcher and Hobson (1932) recognise two levels of laterite at Upper Swan, a high-level laterite about 700 feet above sea-level and a low-level laterite at about 200 feet to 350 feet above sea-level. They write : " The high-level duricrust is seen to grade downwards directly into granite, but at lower levels the duricrust is associated with alluvium and what might be referred to as a ferruginous sandstone. This ferruginous sandstone has also been found associated with the high-level duricrust, but in much smaller quantities." Thus it appears that, although it is not so marked, lateritized ferruginous sandstone occurs at the same level as laterite over the Pre-Cambrian, in places at Upper Swan as well as at Wattle Flat. Fletcher and Hobson regard all the laterite at Upper Swan as having been formed in situ.

From the above considerations and observations of the laterite at Wattle Flat, the following conclusions are submitted :—

(1) All the laterite at Wattle Flat has been formed in situ.

(2) In view of their close association the laterites over the ferruginous sandstone and Pre-Cambrian complex were formed contemporaneously and the differences in character between them are due entirely to the different types of rock over which they are formed.

(3) The occurrence of laterite at random levels and the presence of dipping laterite indicates that its formation did not take place on a perfectly peneplained surface and that in view of this, the significance of the terms high and low-level laterite is lost at Wattle Flat.

(4) Despite Simpson's views to the contrary, the general opinion is that laterite is a residual deposit and that its formation requires a tropical climate of alternating wet and dry seasons. Thus, it would appear that the laterite was formed at a period when the climate of Western Australia was more humid than it is now

3. The Yellow Sand Formation.

This is the youngest formation occurring at Wattle Flat and appears to be comparable to sands described by Prider (1948) at Ridge Hill and by Ivanac (unpublished Mss.) at Gillingarra.

It was seen from mechanical analysis that two types of grains occur in the yellow-sand—rounded frosted grains which tend to be concentrated in the coarser fraction and angular vitreous grains found in the finer grades. As there does not appear to be a transition from one type to the other, it is probable that they have had a different origin.

Accord ng to Twenhofel (1945), wave traction is not very effective in producing rounding in quartz grains from $\frac{1}{4}$ to $\frac{1}{2}$ mm. in diameter and cannot produce frosted surfaces on grains less than 1 mm. in diameter. If this is correct, the presence of fairly well-rounded frosted grains in considerable proportions down to a size of $\frac{1}{4}$ mm. seems to indicate that these grains at least have suffered aeolian transportation.

The heavy mineral suite found in the yellow sand is very similar to that of the ferruginous sandstone, the chief difference being the slightly greater variety of minerals in the yellow sand, which is to be expected in view of their more recent age. Their distributive province is similar to that of the ferruginous sandstone, but the latter shows finer grain, better sorting and different surface textures than are seen in the yellow sand and appear to have been formed in a different way.

The exact origin of the yellow sands cannot be stated definitely, but the indications are that they have a hybrid origin and are part aeolian. This hypothesis is supported by the presence in the yellow-sand of both rounded and euhedral zircons.

VII. SUMMARY OF THE GEOLOGICAL HISTORY OF THE AREA.

(1) In early Archaeozoic times shallow water sediments, arkoses, arkosic grits, sandstones, greywackes and shales were deposited in the basin of a subsiding geosyncline.

(2) As the downbuckling increased, a basic magma was intruded into the sediments as sills or extruded as lava flows.

(3) Then came the period of major orogeny during which the sediments and sills were intensely folded and regionally metamorphosed. This was closely followed by the granitization and associated basification of some of the sediments. An end phase of this granitization was the formation of quartz and pegmatite veins.

(4) The next period of igneous activity was the intrusion of a number of dolerite dykes, possibly either in Archaeozoic or late Proterozoic times.

(5) In Jurassic or Lower Cretaceous times occurred the deposition of the ferruginous sandstone in a lacustrine environment.

(6) Possibly in Miocene times laterite was formed over the Pre-Cambrian complex and the ferruginous sandstone.

(7) Post-dating the period of lateritization and possibly in Pleistocene times was the formation of the yellow sand.

(8) The final stage in the geological history of the area was the formation of recent deposits of alluvium and talus.

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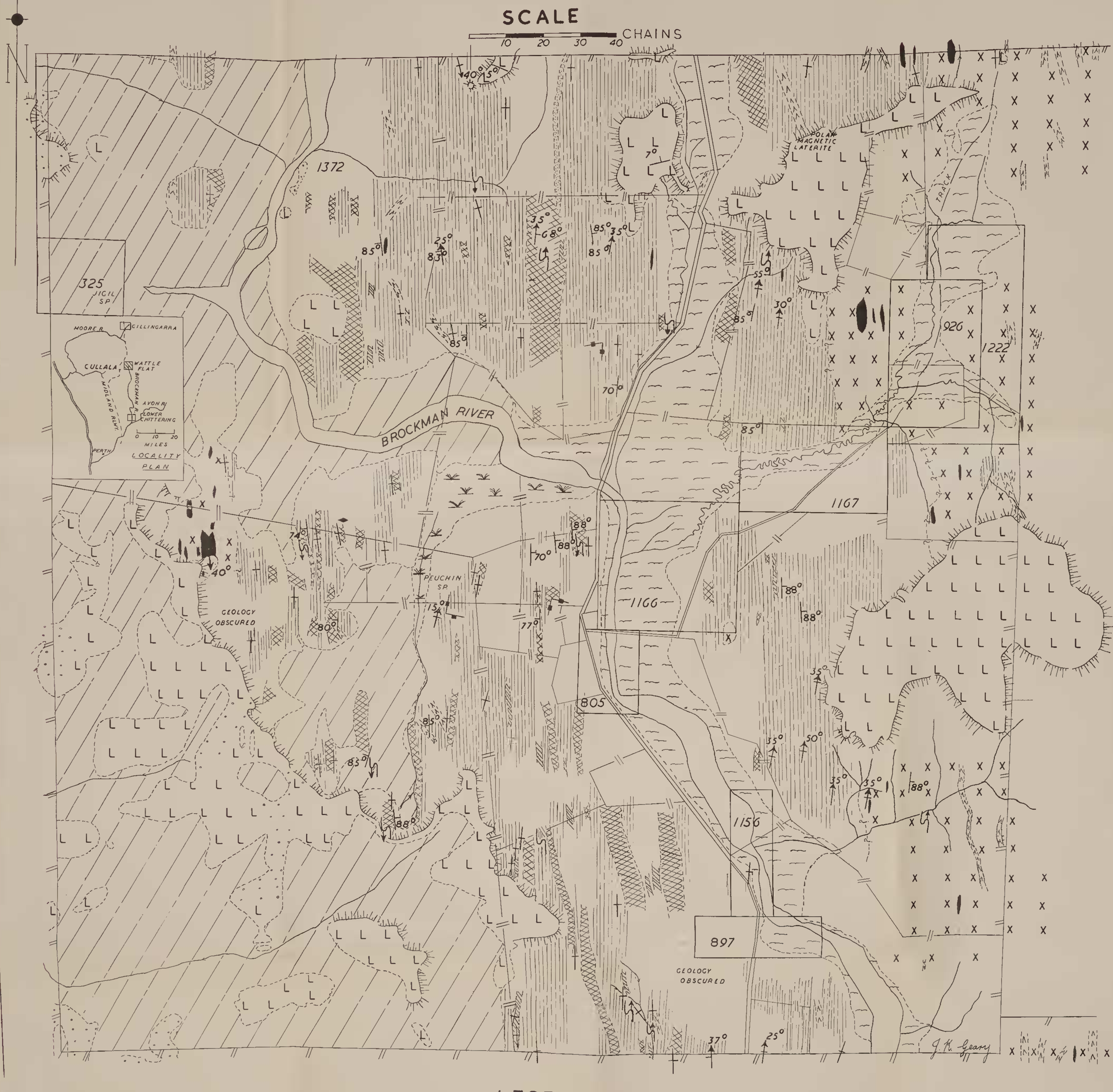
GEOLOGICAL MAP OF THE WATTLE FLAT AREA



LEGEND

ROADS — LOCATION BOUNDARIES — SURVEYED FENCES — UNSURVEYED FENCES

SWAMPY GROUND — BREAKAWAYS — GEOLOGICAL BOUNDARIES — STRIKE AND DIP OF BEDDING 85°

STRIKE OF VERTICAL BEDDING — PITCH OF LINEATION 40° — VERTICAL LINEATION — STRIKE AND DIP OF BEDDING WITH PITCH OF LINEATION 30° 88°

STRIKE AND PITCH OF DRAGFOLDS — STRIKE AND DIP OF JOINTS 75° — VERTICAL JOINTS

ALLUVIUM — YELLOW SAND — LATERITE — FERRUGINOUS SANDSTONE — DOLERITE — GRANITIC GNEISS — BASIC LENSES — HORNBLENDE SCHIST — QUARTZITE — MICA SCHISTS — PLATY GNEISSES